Linac Energy Deviation Correction

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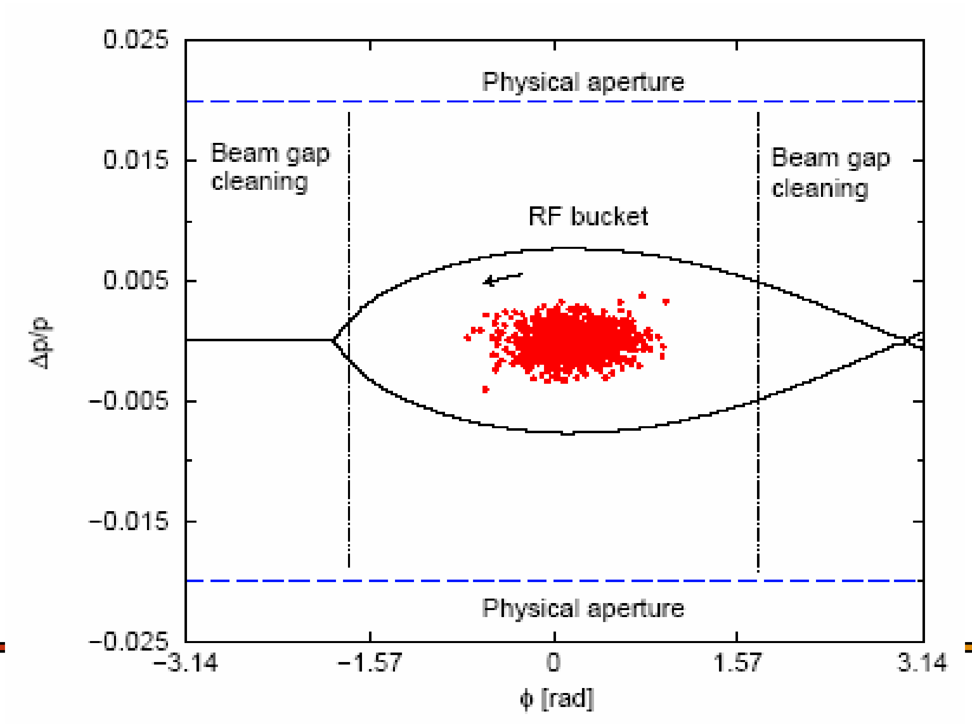
Outline

- Principle overview
  - When is energy correction needed?
  - Energy jitter sources
    - » systematic vs. random
    - » warm section, superconducting RF section
  - Energy correction and phase-space painting
- Design implementation in SNS
- Requirements on a 8 GeV linac

When is energy correction needed?

- When ring activation tolerance would be exceeded due to longitudinal beam halo (1) leaking into beam gap (2) escaping RF bucket (3) hitting momentum aperture (10^{-4} loss tolerance for SNS ring; +/- 1% $\Delta p/p$ momentum aperture)
- When ring instability damping requires controlled momentum spread, ideally obtained with longitudinal phase-space painting (+/- 2.5×10^{-3} $\Delta p/p$ for SNS ring)



Correction & painting with passive RF cavities

- Obtained in SNS with a linac RF cavity detuned (100 kHz) from the resonance frequency (805 MHz)
- "sharpen" the painting pen by reducing momentum spread before injection (~ a factor of 10 ratio)
- Superior to painting the momentum space by modulating the injecting beam energy

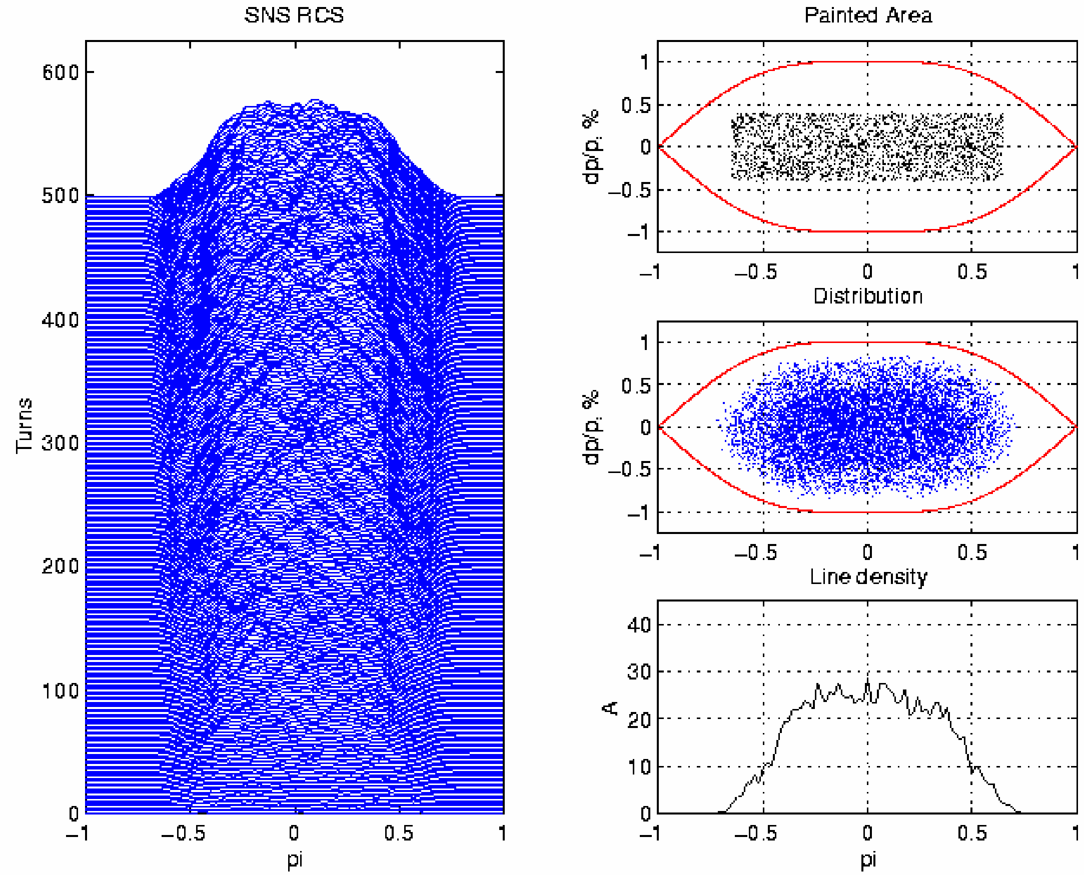
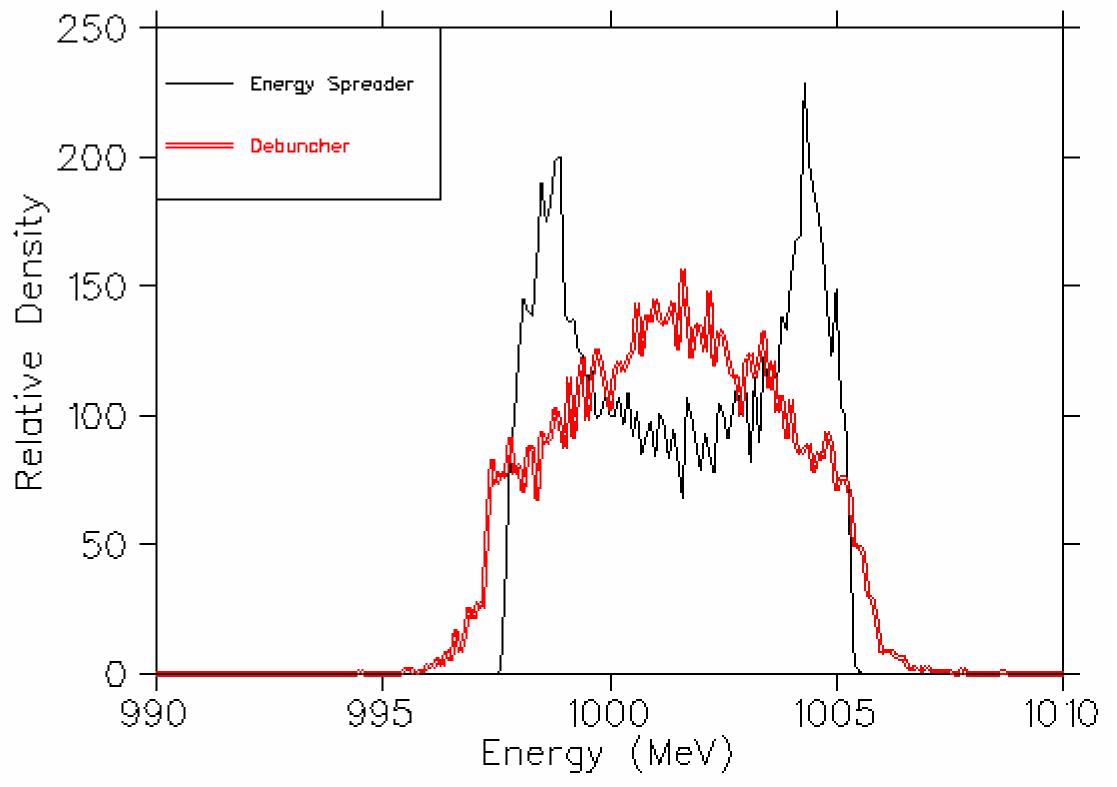


Figure 7: Longitudinal bunch evolution during injection with a dual ($h = 2$ and $h = 4$) RF system. The full injection momentum spread at the end of HEBT line is $\Delta p/p = \pm 0.4\%$, the peak current is 26 A, and the bunching factor is 0.46.

Painting vs. spreading

- Momentum painting: create momentum spread without enhancing momentum tail – in controlled way
- Necessary only if beam tail due to energy jitter and energy spread causes intolerable beam loss and activation



Sources of energy spread & centroid jitter

- Systematic errors
  - Beam loading/transient, space charge & non-equipartition, magnet / cavity error, Lorentz detuning (super-conducting RF linac), static RF cavity control uncertainties
  - Can be mostly compensated by feed-forward
- Random errors
  - Reference line temperature variation, linac injection mismatch, microphonics (super-conducting RF linac), dynamic RF cavity control uncertainties
  - Can not be compensated by feed-forward
- Correction
  - Passive energy-correction cavity
  - Fast feed-back

Linac RF stability survey

- Typical RF stability: 1% in amplitude, 1 degree in phase

$$\delta E_k \approx \sqrt{N_{RF}}\, V_c \left[\left(\frac{\delta V_c}{V_c} \right)^2 \cos^2 \phi_s + (\Delta \phi_s)^2 \sin^2 \phi_s \right]^{1/2}$$

Table I. RF stability for some proton/H^- linacs

Machine	Ipeak (mA)	Freq (MHz)	Design A stab. (%)	Design φ stab. (deg)	Oper. A stab. (%)	Oper. φ stab. (deg)	Remark
LANSCE DTL,CCL	17	201.25, 805	± 1	± 1	± 0.3	± 0.3	1
FNAL DTL,CCL	50	201.25, 805	± 1, ± 0.5	± 1, ± 0.5	± 0.3	± 0.3	2
INR DTL,CCL	12	198.2, 991	± 1, ± 0.7	± 1, ± 0.7	± 0.3	± 0.3	3
CERN DTL	180	202.5	± 1	± 1	± 1	± 1	4
BNL DTL	35-40	201.25	± 0.2	± 0.5	± 0.1	± 0.2	5
ESS DTL,SCL	112	352, 704	± 0.5, 0.5	± 0.5, 0.5	NA	NA	6
KEK/JAERI DTL,CCL	50	324, 972	± 0.3, 0.3	± 0.3, 0.3	NA	NA	7

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RF stability and energy jitter

- The relative energy deviation at the end of linac can be less for a linac of higher energy, given the same energy gain per RF control and the same level of RF control stability
- Number of RF control (N_{RF}) directly determines the final energy deviation

$$\frac{\delta E_k}{E_k} \approx \frac{1}{\sqrt{N_{RF}}}\left[\left(\frac{\delta V_c}{V_c}\right)^2 + \left(\tan\phi_s \Delta\phi_s\right)^2\right]^{1/2}$$

  - N_{RF}: number of cavity/RF control module;
  - $\Delta E \approx V_c \cos\phi_s$ energy gain per RF control module

    $V_c \approx 10$ MeV, $\phi_s \approx 20^o$, $\delta V_c/V_c \approx 1\%$, $\Delta\phi_s \approx 1^o$

  - SNS: $E_k \approx 1$ GeV, $N_{RF} \approx 100$, $\delta E_k/E_k \approx 1.2$ e -3
  - FNAL PD 1-on-1: $E_k \approx 8$ GeV, $N_{RF} \approx 800$, $\delta E_k/E_k \approx 0.4$ e -3
  - 8-on-1: $E_k \approx 8$ GeV, $N_{RF} \approx 100$, $\delta E_k/E_k \approx 1.2$ e -3

Passive energy correction implementation

- As long as phase error at the end of linac is small compared with de-bunching spread, a passive cavity can be used

$$\Delta E_{ec} \approx \frac{\omega_{RF} L}{\beta c} \frac{V_{ec}}{\gamma(\gamma+1)} \frac{\delta E_k}{E_k}$$

$$\delta\phi_s << \frac{\omega_{RF} L}{\beta c} \frac{1}{\gamma(\gamma+1)} \frac{\delta E_k}{E_k} < \frac{\pi}{2}$$

  - V_{ec} voltage of the energy correction cavity
  - ΔE_{ec} energy correction applied

- The distance L needed to realize passive energy correction is a strong function of beam energy

$$LV_{ec} \approx \frac{\beta c \gamma \left(\gamma^2 - 1\right) m_0 c^2}{\omega_{RF}}$$

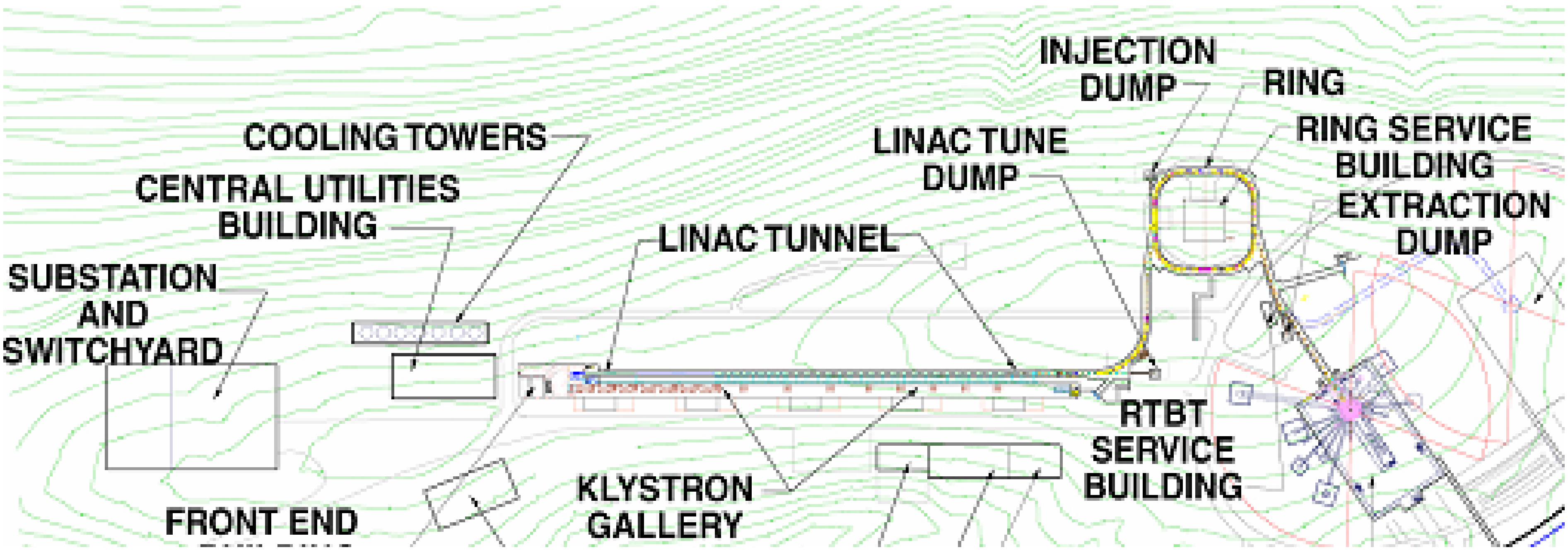
  - SNS: γ = 2.1, f_{RF}=805 MHz, V_{ec}= 3 MV, L=115 m,
  - FNAL PD: γ =9.5, f_{RF}=1.3 GHz, V_{ec}= 20 MV, L=1460 m,

Energy error simulation in SNS

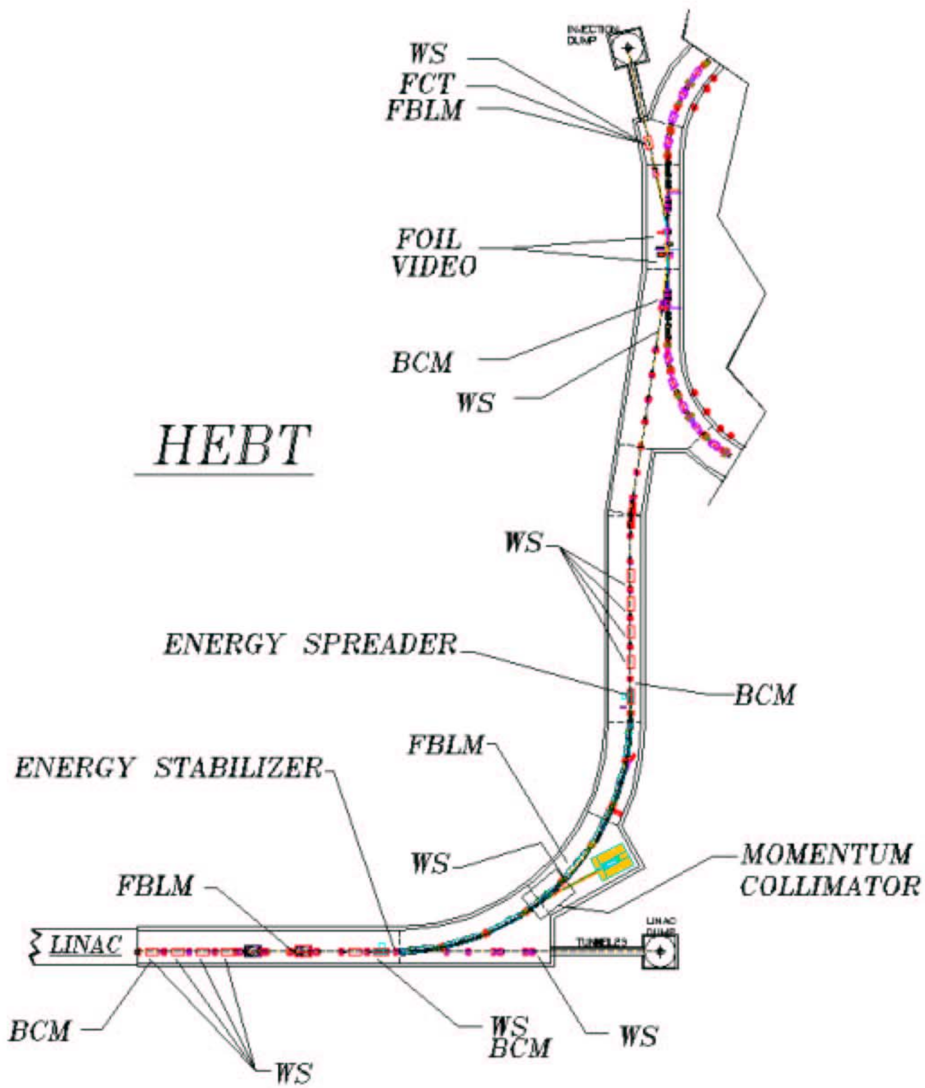
Device	Spread [MeV]	Centroid Jitter [MeV]	Comments
Linac	0.33 (rms)	+/- 1.5	0.5% amplitude, 0.5 deg. phase error (space charge, magnet errors, beam loading/transient, Lorentz detuning, microphonics, non-equipartition)
HEBT collimator	0.72 (rms)	+/- 1.5	space charge growth due to lack of RF
Energy corrector	1.3 -> 0.2(rms)	+/- 1.5 -> +/- 0.2	space charge growth due to lack of RF; cavity corrects the energy error (jitter & spread)
Energy spreader	+/- 4 (full)		cavity broadens the energy core, without enhancing tail
Ring	+/- 10 (full)		gap cleanness versus beam stability

SNS schematic layout

- Three-stage gap cleaning
  - LEBT chopping (65 keV), MEBT chopping (2.5 MeV), Ring beam-in-gap cleaning (1 GeV)
- Collimation at multiple locations, two-stage in ring
  - MEBT scraping with foil, HEBT collimation with foil, ring two-stage collimation, RTBT collimation

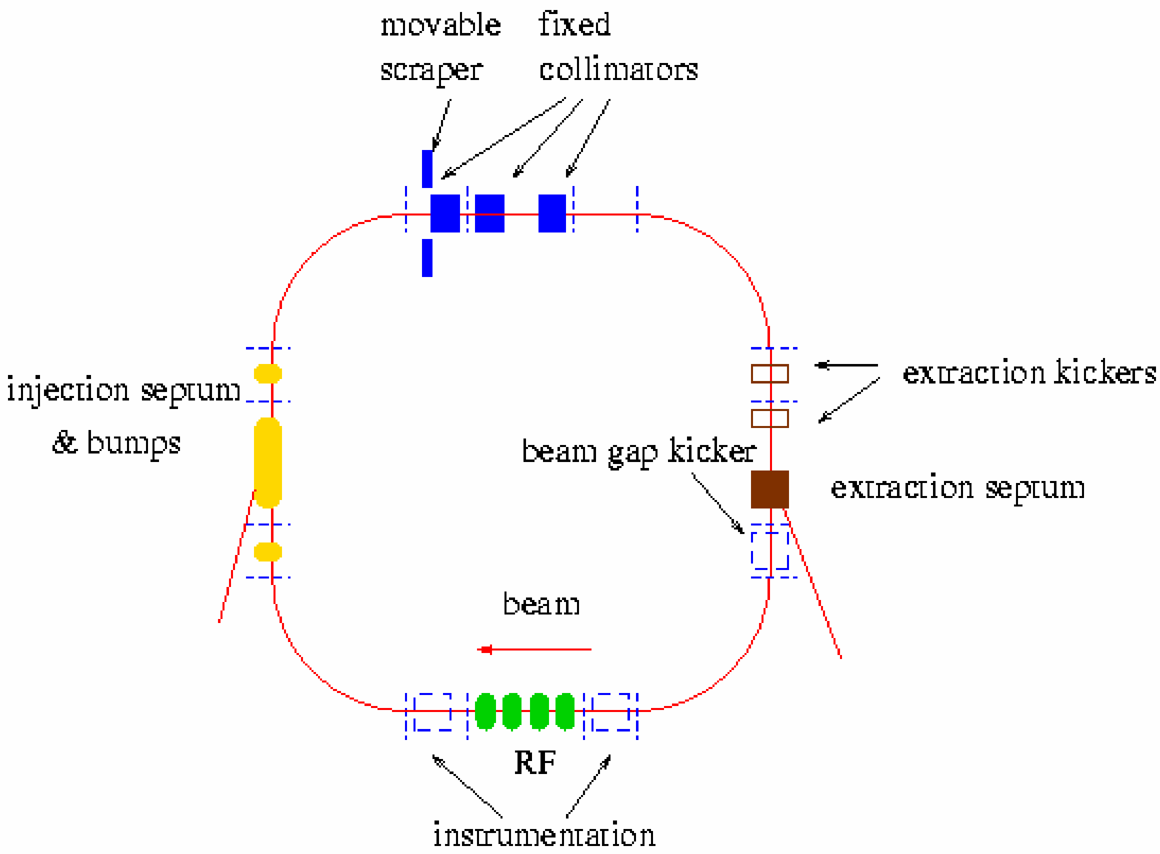


SNS HEBT functions



- Match beam from linac
- Diagnose linac beam
- Clean transverse halo
- Reduce linac energy jitter
- Separate linac and ring operation (first dipole a critical device)
- Clean energy tail / halo
- Paint longitudinal phase space by energy painting
- Match beam to ring for zero-dispersion injection

SNS accumulator ring functions



- Dedicated collimation section
- No energy ramping
- Long straight-section, large aperture
  - Injection flexibility
  - Collimation efficiency
- Four straight-sections for four functions
  - Injection;
  - RF;
  - Collimation;
  - Extraction
  - Diagnostics all-around
- Dispersion-free injection
  - Decoupled H, V, L

Summary

- Energy correction for a high-energy linac is challenging; and it's not obviously needed for FNAL PD
  - Don't do it if one doesn't have to
- Stabilize the linac RF as much as one can
  - Control of superconducting RF cavities: one-klystron-per-cavity or fast phase shifter at high power
  - Stabilization of reference line
  - Feed-forward on beam loading, Lorentz detuning, etc.
  - Possible fast feed-back
- Alleviate the demand on energy correction by ring implementations
  - Adequate momentum aperture for beam stability
  - Efficient collimation
  - Efficient beam gap cleaning
- or, other crazy options →

How about a 5 GeV linac?

- Space charge limit
  - $\Delta \nu_{x,y} \sim \beta^{-2}\gamma^{-3}$ 5 GeV: g=6.3; 8 GeV: g=9.5
  - Needs at most a factor of 3.4 increase in the combination of repetition rate & MI output energy to reach the same power
- Tolerable with H- stripping
  - Tolerable blackbody radiation
- Less activation
  - A factor of 1.5 lower
- Energy correction do-able
  - 850 m drift distance, 10 MV peak voltage can do the job
- Much higher magnetic field can be used
  - 500 G -> 800 G; B higher by x1.5, BL lower by x1.5
  - Magnet length 6 m -> 2.6 m

Estimated loss & activation in SNS

Item	Controlled loss	Uncontrolled loss		Beam-off residual	Beam-on		
	(fractional)	(fractional)		activation [rem/h]	heat load	damage	background
	(integral)	(integral)	(loss/meter)	(4 h down; 30 cm)	[Watt]	[rad/h]	
IS/LEBT charge exchange		~0.1		none			
LEBT chopper	0.277			none			
LEBT beam recombination		< 0.005		none			
RFQ transmission		0.08		none			
MEBT chopper	0.042			none			
MEBT beam recombination		< 0.005		none			
Linac H- gas stripping			< 1.e-7/m		< 0.2 W/m		
Linac (warm)			< 2.5e-6/m	< 0.1	< 1 W/m		
Linac (SRF)			< 5.e-7/m	< 0.1	< 1 W/m		
HEBT collimators	1.e-3	1.e-5			2 kW		
HEBT H- magnetic stripping			< 1.e-8/m		< 0.02 W/m		
HEBT H- stripping			< 1.e-7/m		< 0.2 W/m		
Ring foil miss	0.02 - 0.1				40 - 200 kW		
Ring foil nuclear scattering		3.e-5			60 W		
Ring collimation section	2.e-3	1.4e-4		6.3 - 9.9	4 kW	100 - 1500	
Ring extraction section			< 5.e-7/m	< 0.1	< 1 W/m		
Ring arc section			< 5.e-7/m	< 0.1	< 1 W/m		
Ring rf section			< 5.e-7/m	< 0.1	< 1 W/m		
RTBT collimation region		1.e-6			2 W		
RTBT (non-collimation)							
Target window		0.04			80 kW		
Goal	0.1		5.e-7/m				